Thermo- and Chemo-Dynamics of Simulated Galaxy Clusters

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(I) X-ray scaling relations & ICM thermodynamics;

(II) Including chemical evolution in simulations:

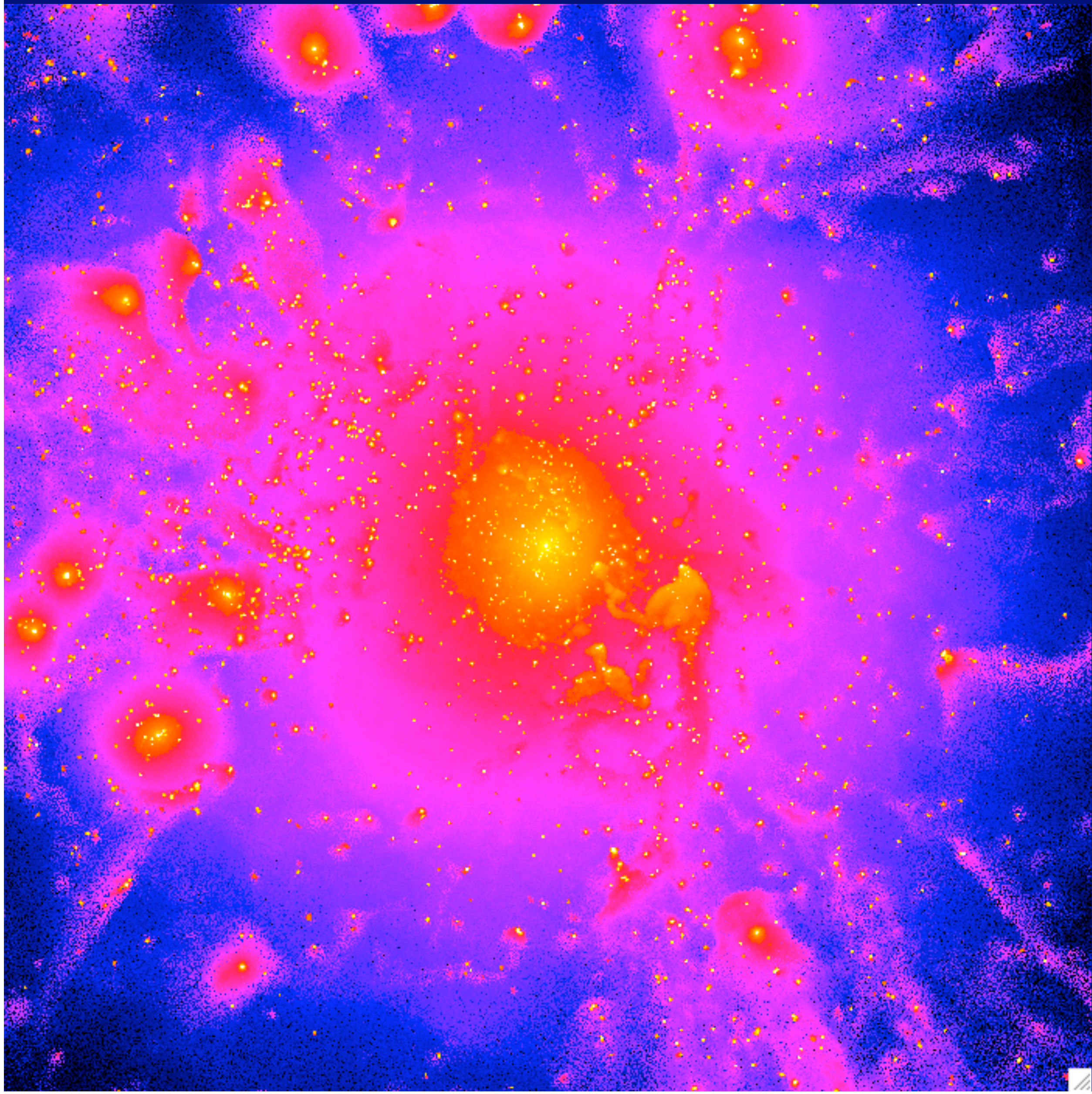
- II.a Metal Enrichment of the ICM;
- II.b Optical/near-IR properties of the galaxies.

(III) The effect of AGN feedback.

Collaborators: K. Dolag, S. Ettori, D. Fabjan, G. Murante, E. Rasia, A. Saro, L. Tornatore

Talk @ "The Warm & Hot Universe", New York, May 7th-9th 2008

Different strategies to simulate clusters



SB, Dolag et al. 08;
Dolag, SB et al. 08,
for reviews

Examples with Tree+SPH
GADGET-2; Springel '05

<u>SB et al. '08</u>

$L = 75\ h^{-1}$ Mpc

$N_{gas} = N_{DM} = 512^3$

$\varepsilon_{Pl} = 2.1\ h^{-1}$ kpc

SF + SN + metals

<u>Dolag et al. '07</u>

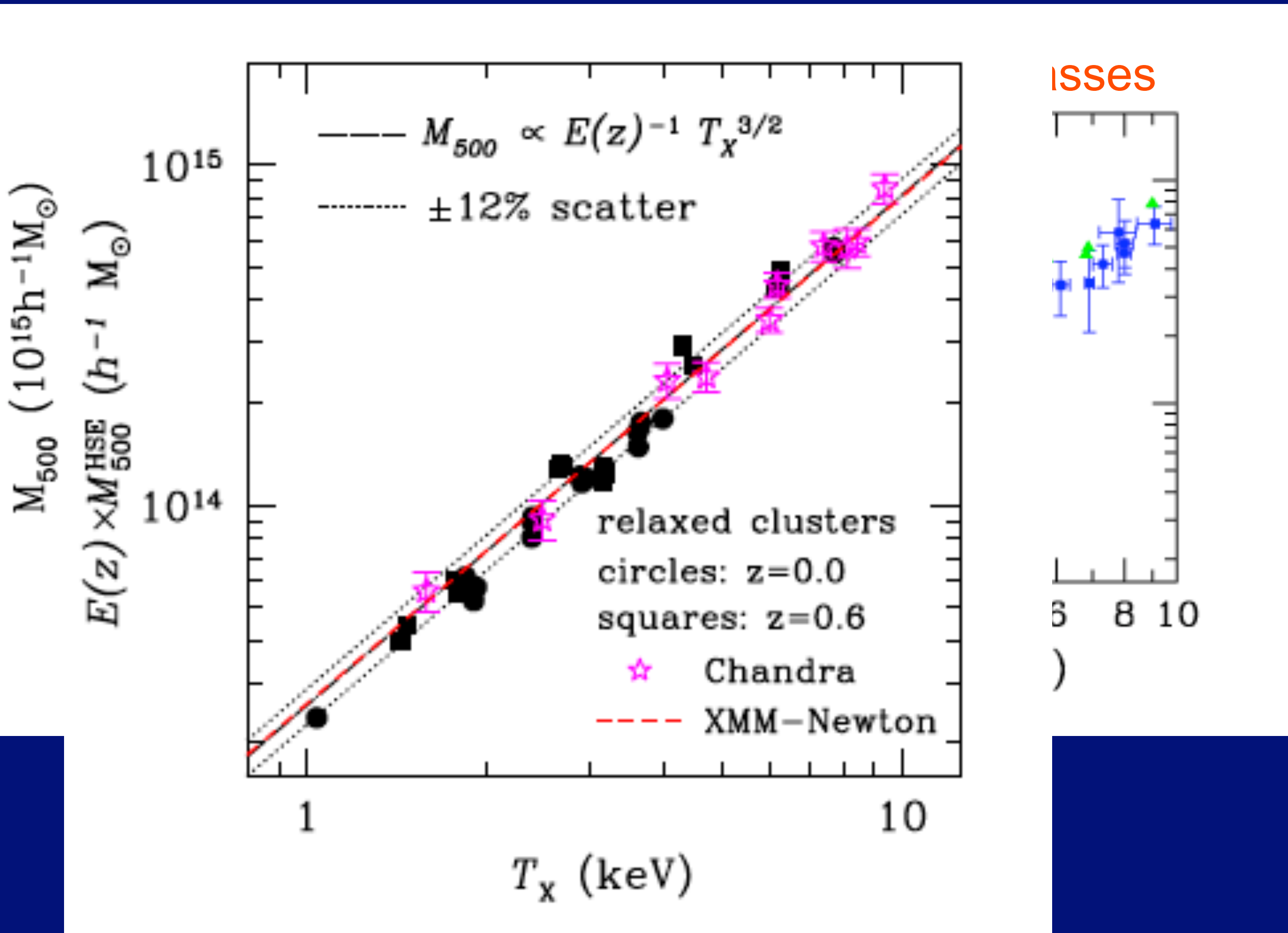
$M \sim 2\ 10^{15}\ h^{-1}\ M_{\odot}$

$N_{gas} = N_{DM} \sim 10^7$

$\varepsilon_{Pl} = 2.5\ h^{-1}$ kpc

SF + SN + metals

The mass-temperature relation



SB et al. 04
Rasia et al. '05

Use the βγ-model for the ICM + hydrostatic equilibrium:
(Finoguenov et al. '01; Ettori et al. '03)

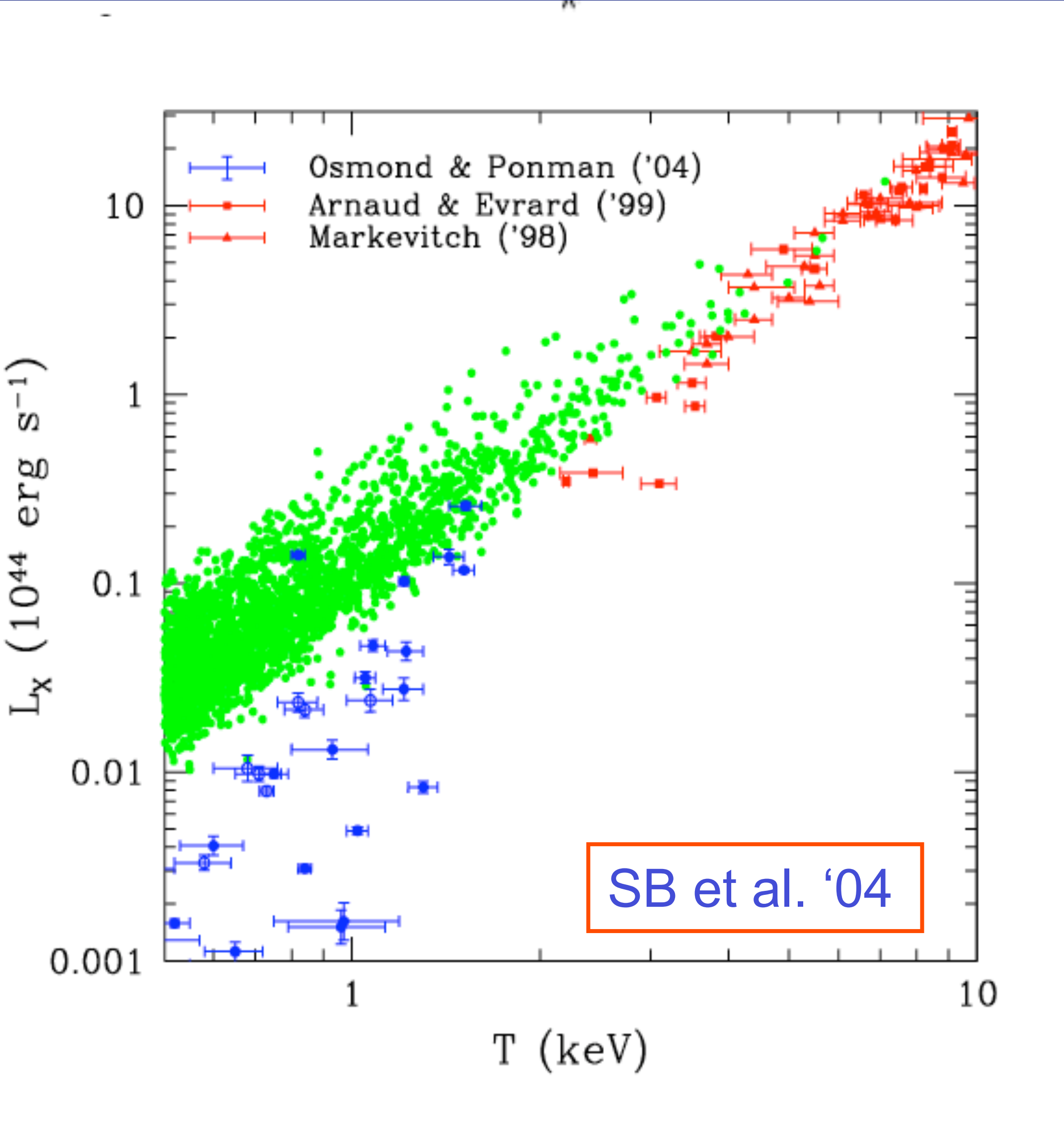
Nagai et al. '07

Carry out the same mass estimates as in Chandra data

(Vikhlinin et al. '05)

Good agreement between simulated and observed M-T, once hydrostatic mass estimates used in simulations.

The Luminosity-Temperature relation



Δαϖè ετ αλ. '02: cooling only

L_X-T relation reasonable, but up to 80% of baryons in stars for groups!

Muanwong et al '03: cooling + pre-heating

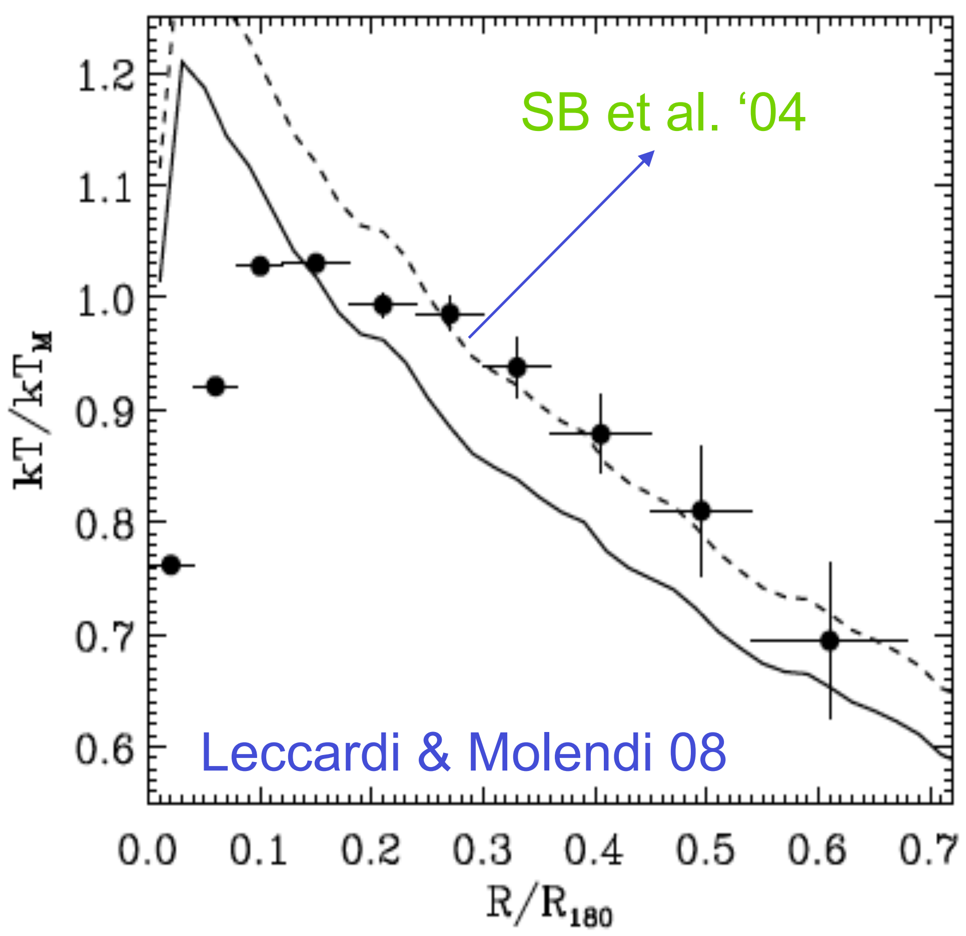
No much bending at the scale of groups.

SB et al '04: cooling + SF + galactic winds

⇒ ~ OK above 2 keV

⇒ Over-luminous groups and too small scatter.

The Temperature Profiles



Tornatore et al. '03; SB ετ αλ. '04; Roncarelli et al. '07; Kay et al. '07: cooling + SF + galactic winds (SPH);

Loken et al. '02; Nagai ετ αλ. '07: cooling + SF + SN feedback (AMR):

- Cooling steepens T-profiles at the centre;
- Wrong in the core regions
- OK at larger radii.

Pratt et al. '07; Leccardi & Molendi '08: analysis of XMM data.

Agreement with simulations outside the cool core region.

Hydro simulations of the ICM enrichment

Tornatore et al. '04, '07; Fabjan et al.'08
SB, Fabjan, Tornatore et al. '08 for a review

Implementation in the GADGET-2 code (Springel '05)

Model parameters:

(a) IMF; a.1 Power-law IMF: $\phi(m) \sim m^{-(1+x)}$ x=1.35: Salpeter 55; x=0.95: Arimoto Yoshii 89

a.2 Multi-slope IMF (Kroupa 01)

(b) Stellar lifetimes: Padovani & Matteucci '93; Maeder & Meynet '89

(c) Metallicity-dependent stellar yields (SN-Ia, SN-II and AGB)

(d) Velocity of galactic winds: v_w=500 km s^{-1} (normal winds)

v_w=1000 km s^{-1} (strong winds; AY IMF)

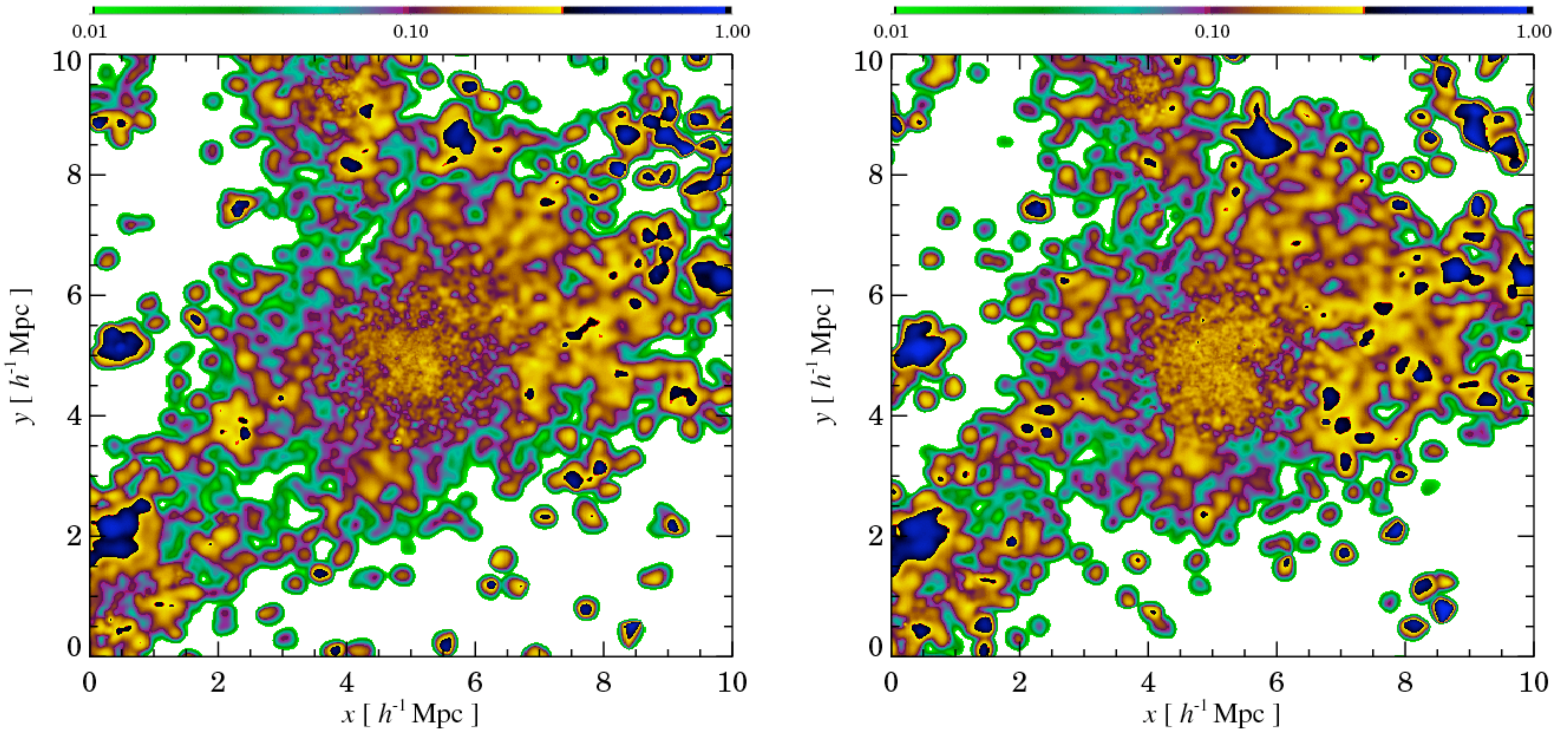
Simulated clusters: 9 Lagrangian regions (Dolag et al. '08) containing 19 "clean" clusters with $M_{vir} = (5 \times 10^{13} - 2 \times 10^{15}\ h^{-1} M_{sun})$

Maps of Iron distribution

Tornatore et al. '07

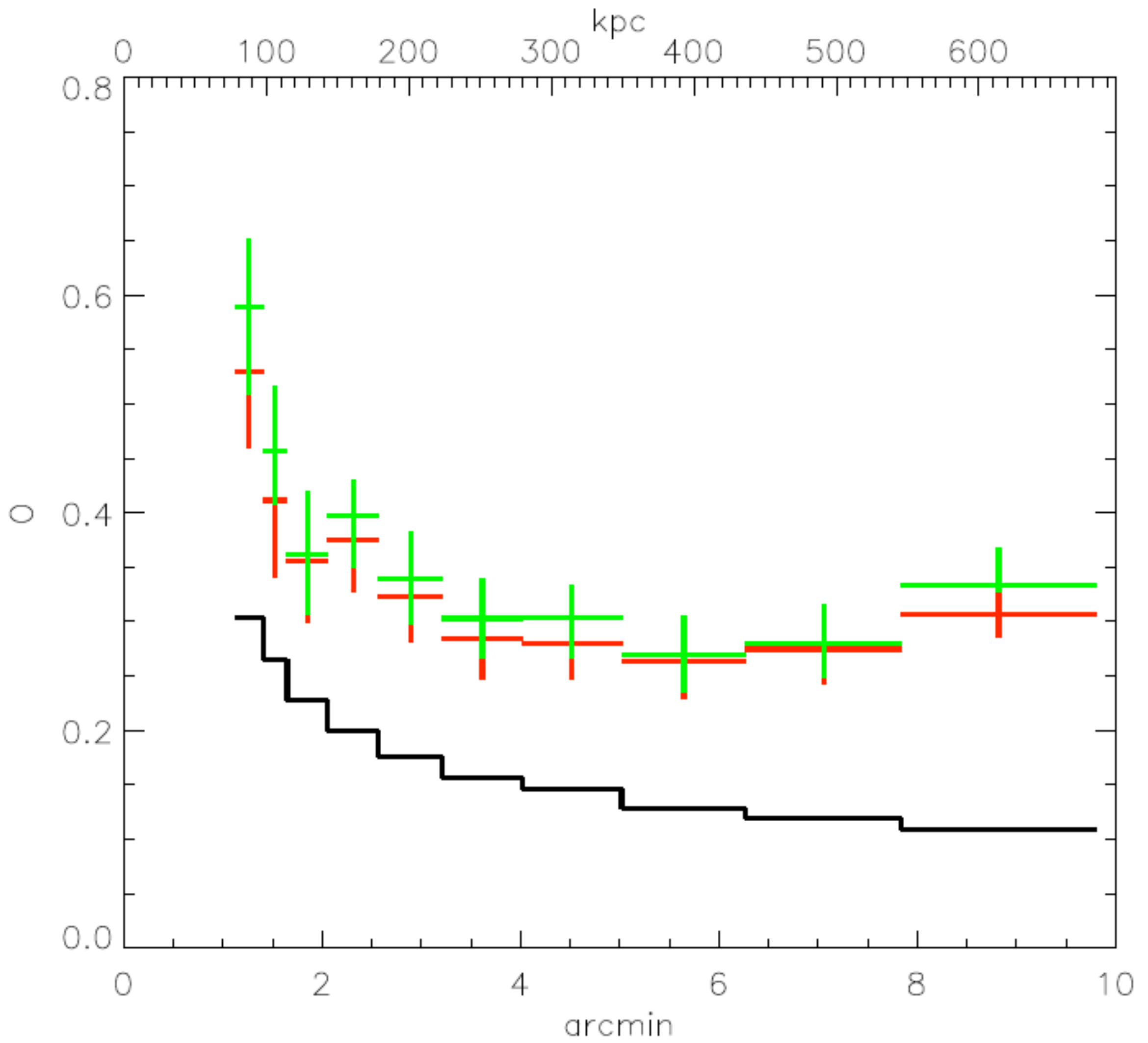
Salpeter IMF

Top-heavy IMF



Mock X-ray observations of ICM metallicity

Rasia et al. 2007



1 Ms exposure of a ~8 keV cluster

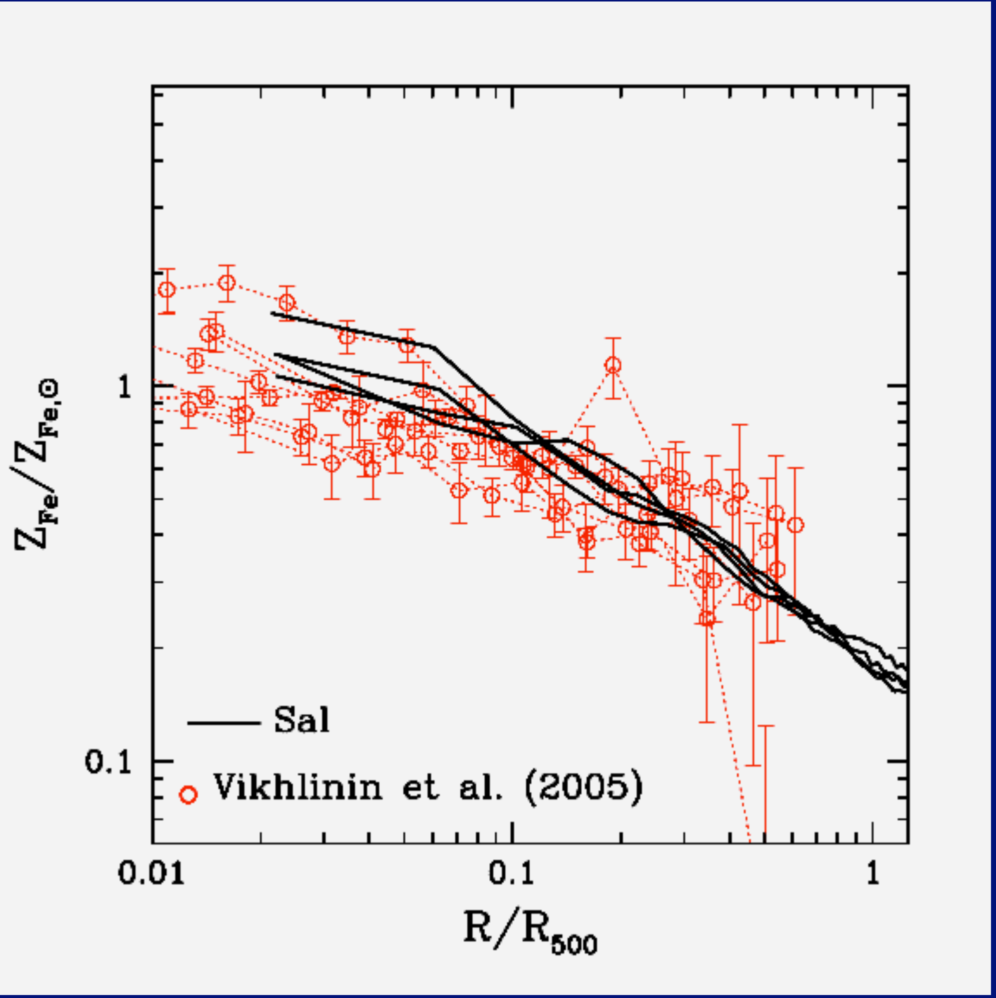
⇒ EW and spect. estimators of Z_{Fe} and Z_{Si} quite close to each other (unlike T_{ew} and T_{spec}).

⇒ Spect. measurement overestimates Z_O:

- Due to the multi-component nature of the ICM.
- Bias related to the limited XMM spectral resolution.

Profiles of Iron Abundance

Fabjan et al. '08

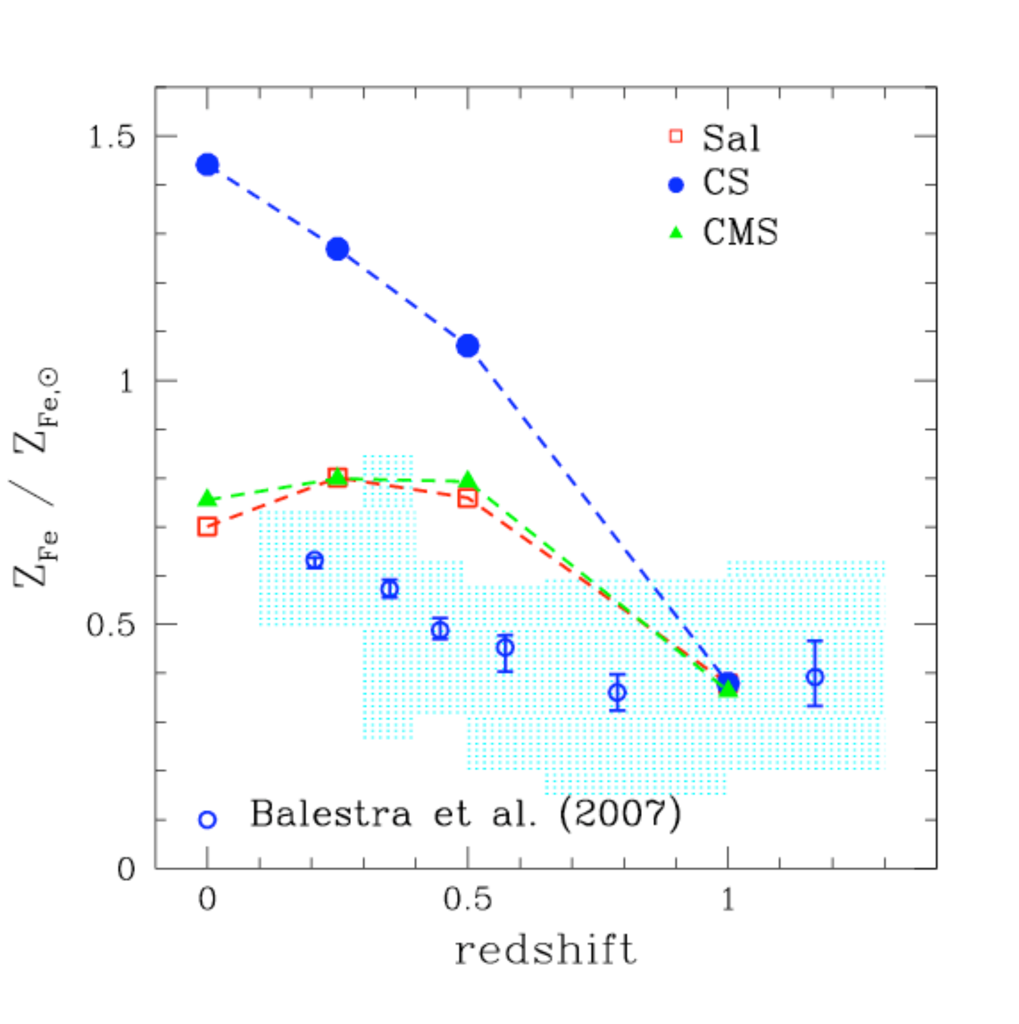


Vikhlinin et al. '05: Chandra observations of 16 nearby relaxed clusters

1. Agreement with the slope from Chandra data.
2. Preference for a standard Salpeter IMF
3. Flattening at $>0.1R_{500}$ (XMM: Snowden et al. 07) never predicted

- Highly desirable: comparison btw Chandra & XMM results.

Evolution of the ICM metallicity



Observational data from Chandra archive:
Balestra et al. '07
Maughan et al. '08

- Metallicity evolution naturally produced.
- Test: halt by hand SF at z=1.

⇒ Metals produced at lower z by long-lived stars

⇒ Far too strong metallicity evolution

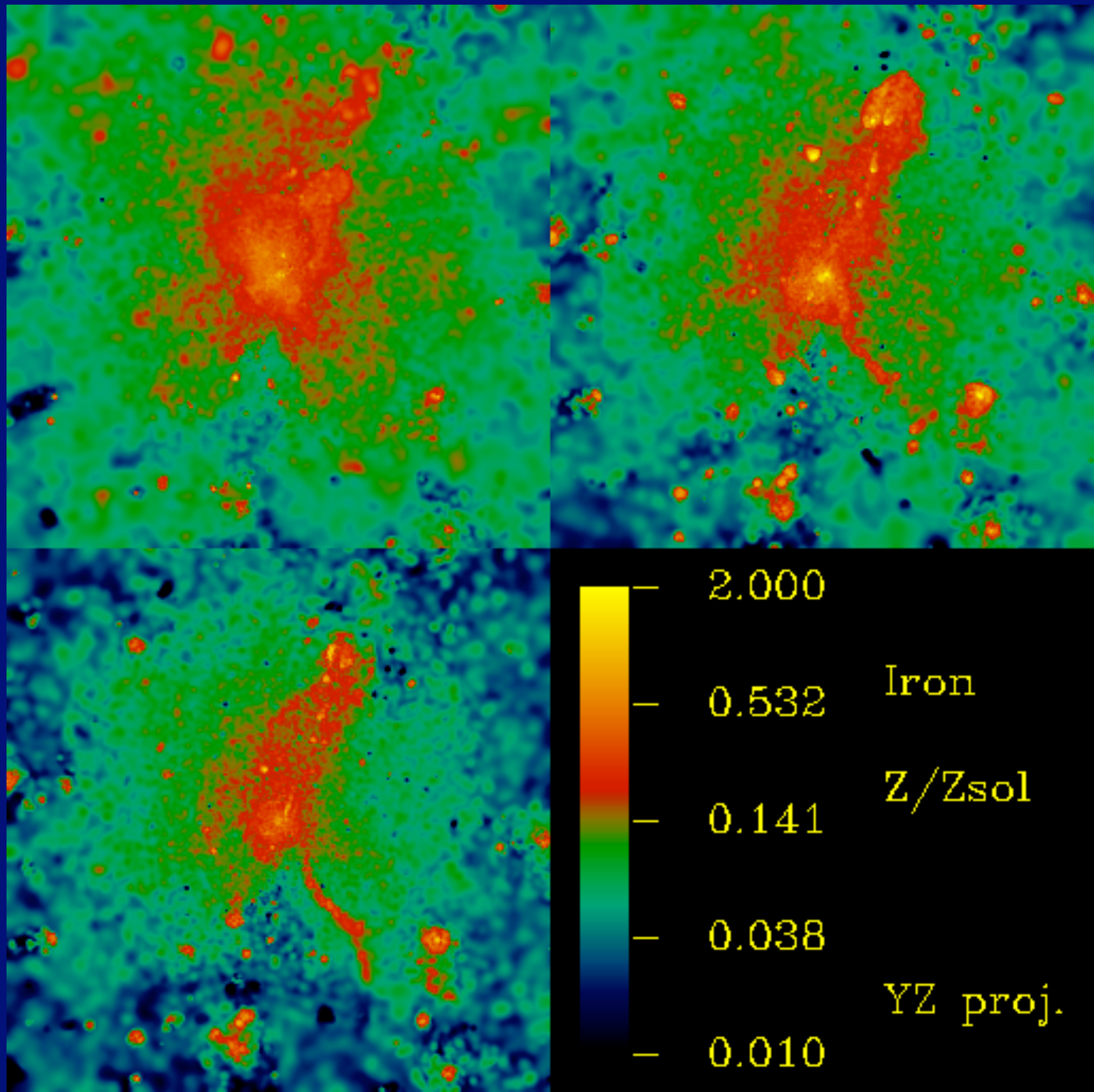
⇒ Need residual low-z SF to "eat" metals in high-density regions.

Evolution of the ICM metallicity

Reference run

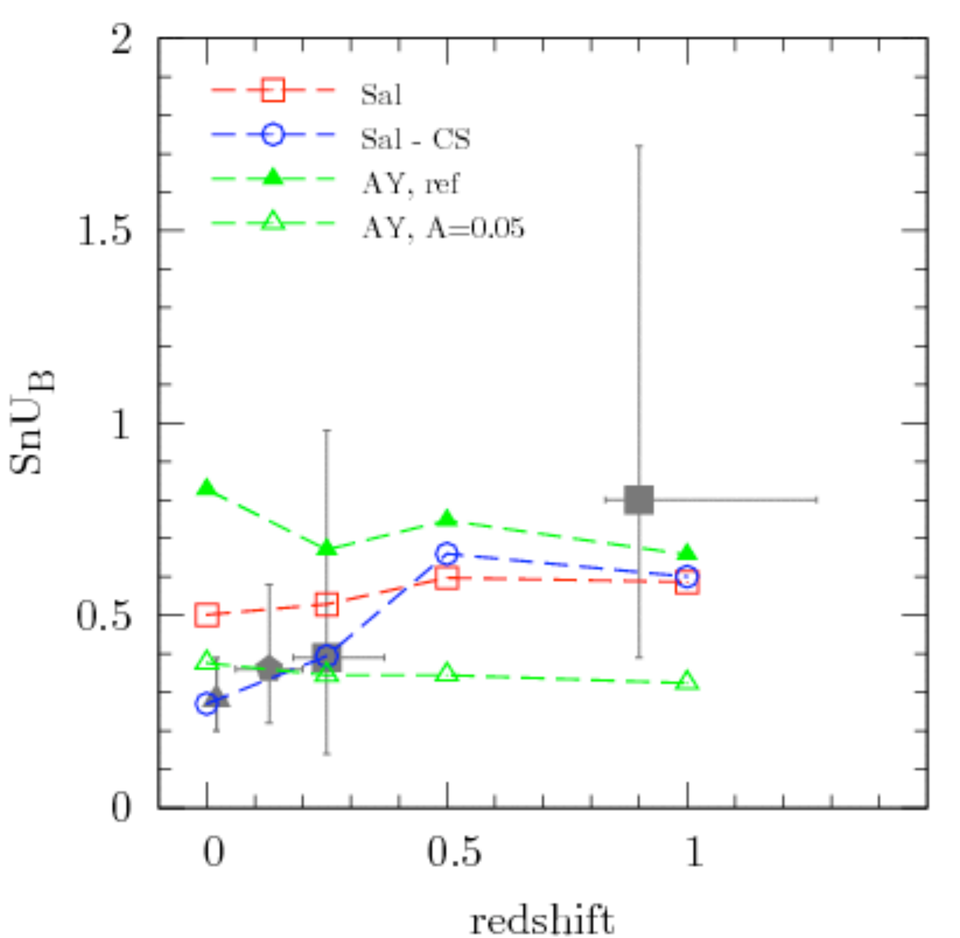
SF stopped at z=1

SF & metals stopped at z=1



The Sn-Ia rate

Rate of Sn-Ia per unit B-band luminosity



Observational data:

z ~ 0: Mannucci et al. 07

z ~ 1.2: Sharon et al. 07

z ~ 0.2-0.9: Gal-Yam et al. 07

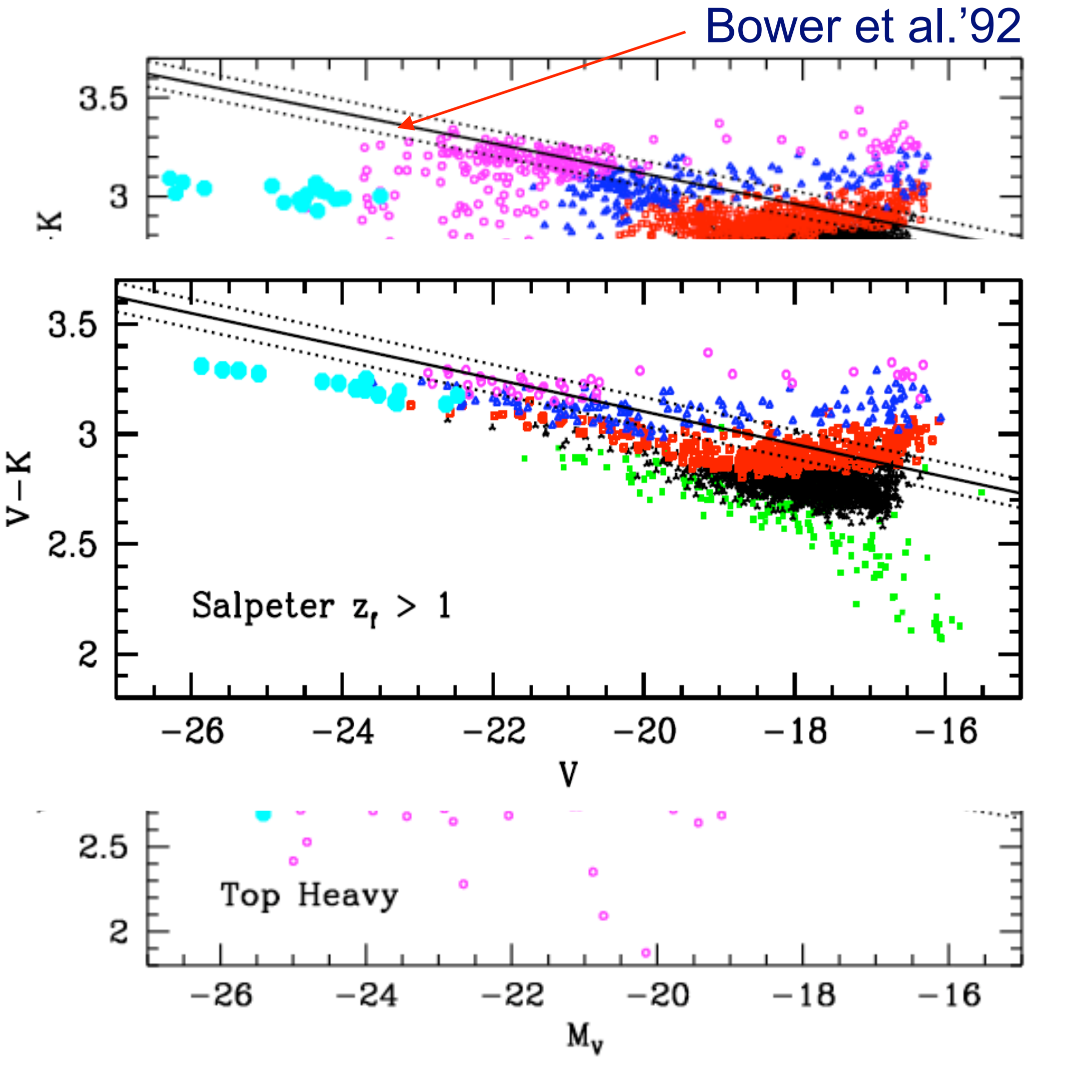
⇒ Salpeter IMF favoured by low-z data

⇒ Too high low-z rate from excess of recent SF

⇒ Better agreement if SF quenched at z<1.

The Color-Magnitude Diagram

Saro et al. '06



1. The CMR is given by a metallicity sequence.
2. Closer to the observed relation for a Salpeter IMF
3. BCGs always much bluer than expected

⇒ Too much ongoing star formation in the BCGs

⇒ Need to quench SF at z<1.

Feedback from BH accretion in GADGET

Springel, Di Matteo & Hernquist (2005).

- Bondi accretion rate (related to the large-scale properties of the gas distribution), with Eddington limit:

$$\dot{M}_{\rm B} = \frac{4\pi\alpha\, G^2 M_{\rm BH}^2\, \rho}{\left(c_{\rm s}^2 + v^2\right)^{3/2}}$$

$$\dot{M}_{\rm Edd} \equiv \frac{4\pi\, G\, M_{\rm BH}\, m_{\rm p}}{\epsilon_{\rm r}\, \sigma_{\rm T}\, c}$$

$$\epsilon_{\rm r} = \frac{L_{\rm r}}{\dot{M}_{\rm BH}\, c^2}$$

: radiative efficiency

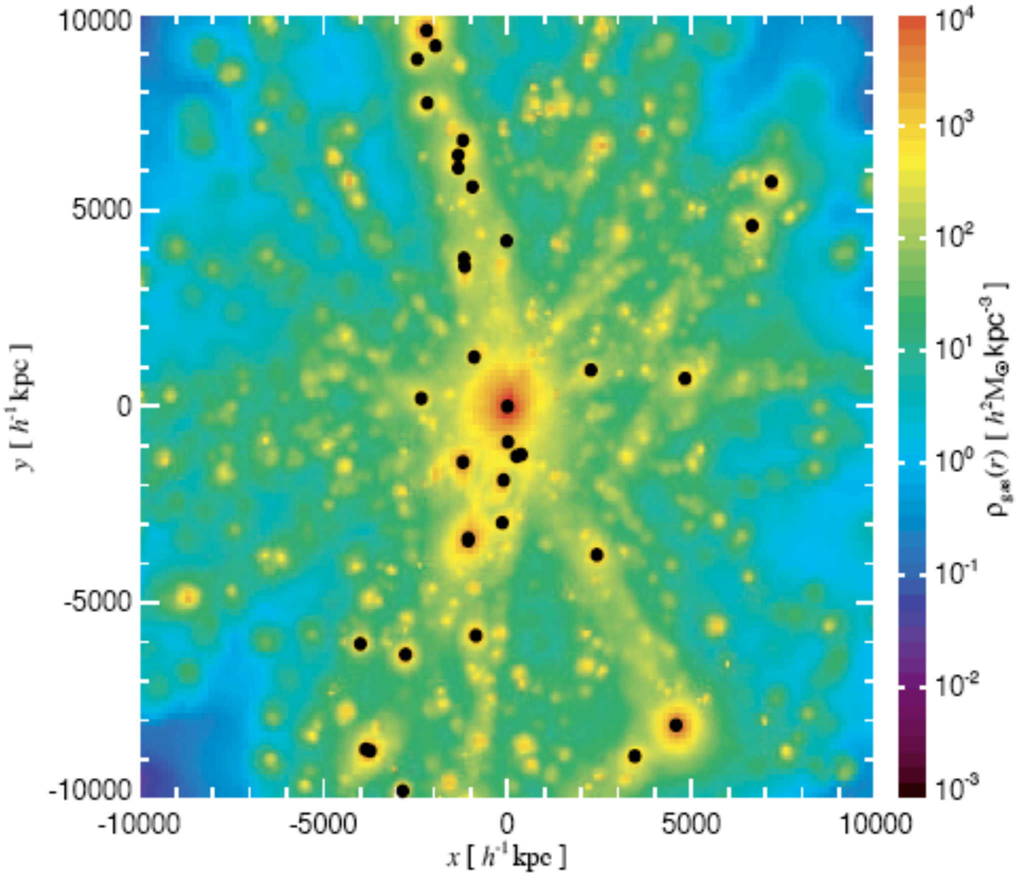
$$\dot{E}_{\rm feed} = \epsilon_{\rm f}\, L_{\rm r} = \epsilon_{\rm f}\, \epsilon_{\rm r}\, \dot{M}_{\rm BH}\, c^2$$

: thermalized energy

- Seed BHs with initial mass of 10^5 $M_{\odot}$
- BHs accrete mass by swallowing of gas particles and merging.

The effect of AGN feedback

Sijacki et al. '07

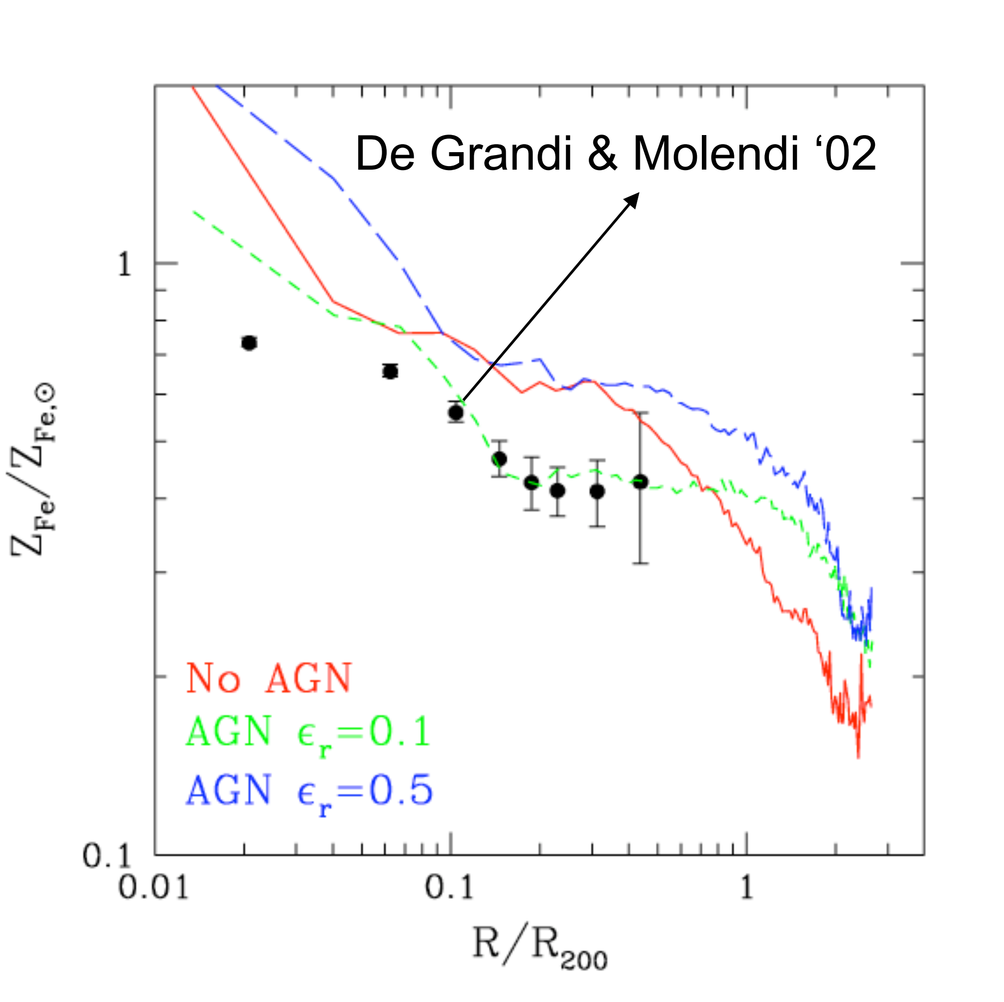


- "Self-consistent" BH feedback"
- "QSO mode": low-efficiency thermal feedback
- "Radio mode": energy in inflating bubbles.

(see talk by E. Puchwein)

The effect of the BH feedback

Fabjan et al. ‘08



- Couple the BH feedback by Springel et al. ‘05 with the metal enrichment scheme.

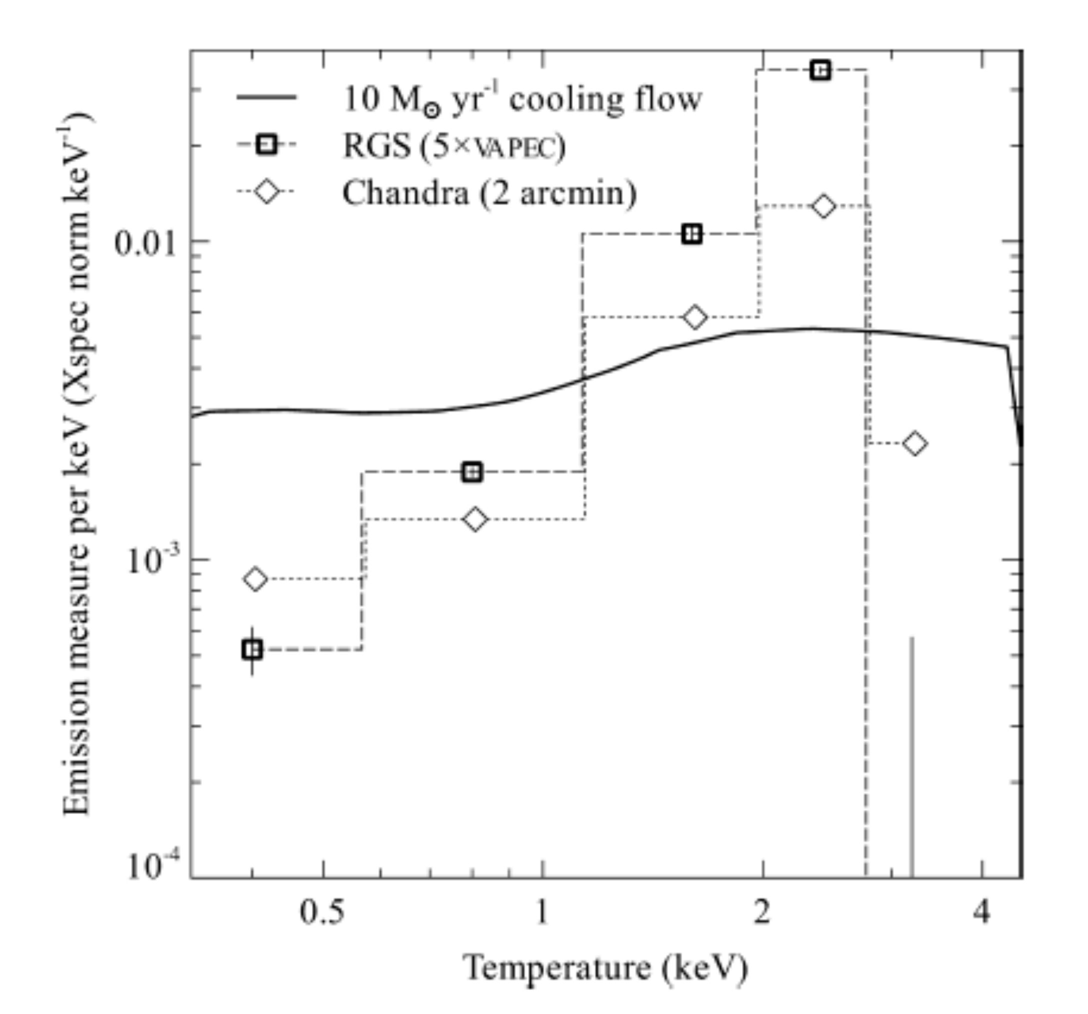
⇒ Quench star formation at z<3

⇒ Suppression of the temperature spike;

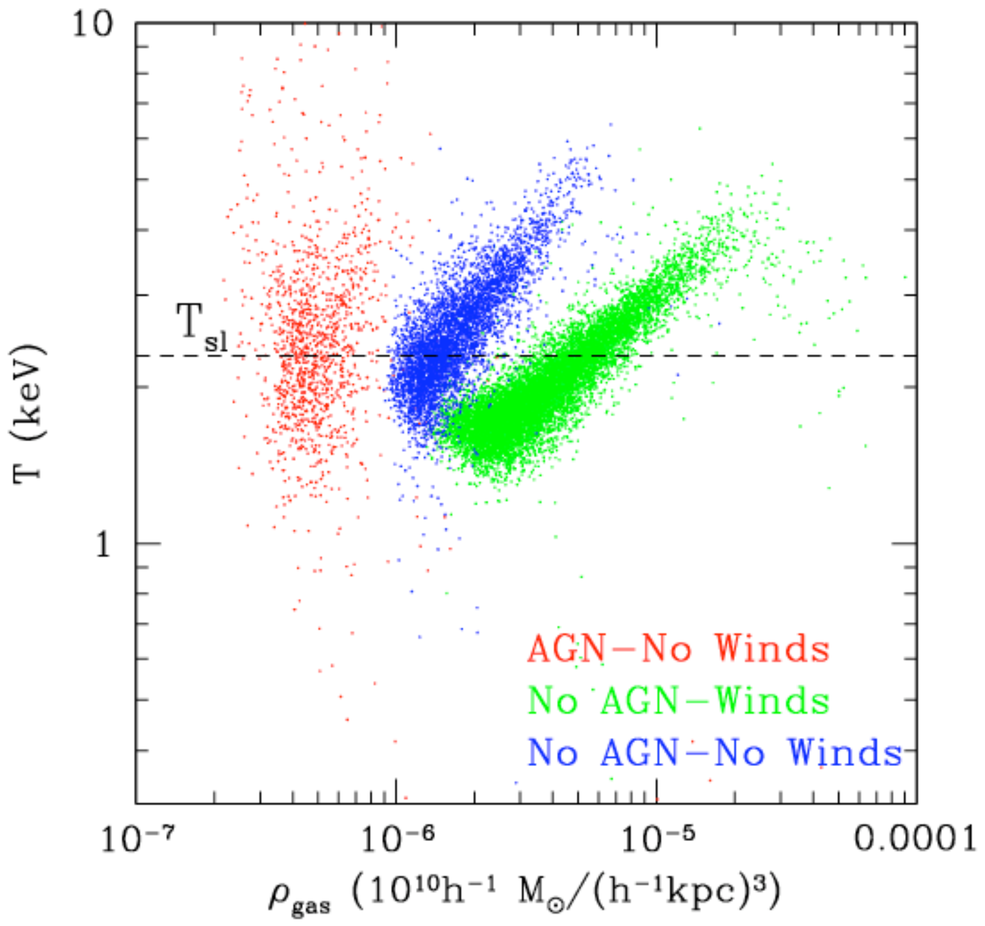
⇒ Increase of the central entropy;

⇒ Flattening of the metallicity profiles for $R>0.2R_{200}$.

Producing the “cool core” structure



AGN feedback: phase diagram



$M_{vir} = 1.0 \times 10^{14}\ h^{-1}\ M_{sun}$

Gas within $0.2\ R_{vir}$

⇒ Simulations naturally predict the lack of gas at $T<0.5\ T_{vir}$

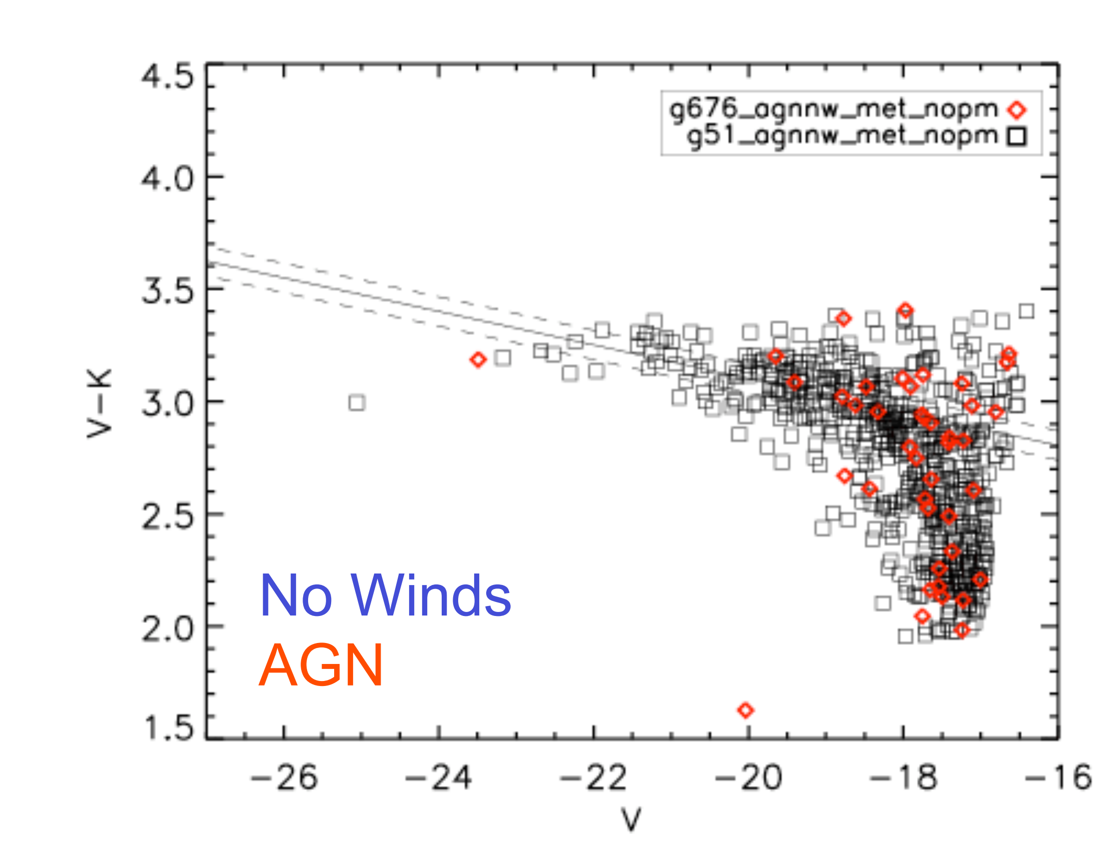
⇒ Galactic winds: bring gas on a lower adiabat;

Negative T-profiles still present

⇒ AGN feedback: strong suppression of central density

~ no trend of ρ_{gas} with T.

The effect of the BH feedback



Effect on the CMR:

- Make it bluer, due to lower metallicity of galaxies;
- BCGs older but still blue, due to a lower metallicity.

Need to model the transition from the QSO to the "radio" mode: more efficient to quench SF in BCGs!

Conclusions

(a) Simulations are doing remarkably well outside cool-cores.

(b) Inner temperature profiles & BCG colors $\Rightarrow$ wrong cool cores.

(c) Profiles and evolution of Z_{Fe} nearly OK.

$\Rightarrow$ Shall we trust them until we have the right galaxies?

(d) Suppress low-z star formation: required by the CMR and by the Sn-Ia rate.

Need to be gentle $\Rightarrow$ Prevent too strong metallicity evolution.

(e) AGN feedback goes in the right direction. BUT:

$\Rightarrow$ Need to better understand cross-talk between widely different (~1 pc vs. >100 kpc) scales;

$\Rightarrow$ Relative importance of different channels for energy thermalization.